SECTION 1

ROADMAP FOR TROPICAL CYCLONE RESEARCH TO MEET OPERATIONAL NEEDS

INTRODUCTION

The 2005 hurricane season in the North Atlantic and Caribbean region set records for damage to the U.S. mainland. Although the 2006 hurricane season has not been as active as the 2005 season, landfalling hurricanes continue to be a threat to a large segment of our population due to the increase in density and economic infrastructure in coastal regions and the potential havoc these severe cyclonic storms can have inland due to tornadoes and flooding related to the decaying tropical cyclone (TC).

On July 10, 2005, Hurricane Dennis made landfall near Pensacola, Florida, with 105-knots winds and 10-foot storm surges. Florida residents were not strangers to hurricanes, as this was the fifth hurricane to hit Florida in less than a year. On August 25, 2005, Hurricane Katrina killed 14 in southeastern Florida when it brought heavy rains and winds to that region. On August 29th-30th, Katrina blasted the Louisiana and Mississippi coasts, coming onshore just east of New Orleans (Figure 1-1). Katrina's winds and massive flooding left thousands homeless, 2.3 million without electricity, roads and bridges destroyed, and communications inoperable. The storm surge caused by Katrina swamped the Mississippi Gulf Coast, destroying hundreds of homes, roads, and much of the coastal infrastructure. In Hurricane Katrina's wake, the estimated direct fatalities were 1,353, making it the third deadliest hurricane in the United States[1]. In addition to the catastrophic loss of life, Katrina also caused approximately $100 billion in losses.

Hurricane Rita struck the Florida Keys and the Gulf Coast in September following Katrina. On September 20, 2005, Hurricane Rita dumped heavy rains on the Florida Keys. It reached category 5 strength over the central Gulf of Mexico, but eventually weakened prior to making landfall as a category 3 hurricane at Sabine Pass near the Texas-Louisiana border. The strong storm surge and heavy winds caused major damage in the Louisiana and Texas coastal areas. Then, from October 18th to 24th, Hurricane Wilma ravaged Haiti, Jamaica, Cozumel, Cancun, Playa del Carmen, and eventually southern Florida. At one point, Wilma strengthened to category 5 on the Saffir-Simpson intensity scale for TCs, and on October 19th it became the deepest (lowest pressure) hurricane on record in the Atlantic, with a pressure dropping to 882 millibars. Wilma was the fourth storm in the 2005 season to reach category 5.

Operational forecast and warning capabilities require specialized atmospheric and oceanic observations from many platforms and sensors-both in situ and remote (Figure 1-2); specialized numerical weather prediction (NWP) models; highly trained people to develop and disseminate forecasts and warnings; and an active outreach program. Operational capabilities in each step of this end-to-end system have improved significantly since the inception of TC forecasting. The gains made over the past several decades in our understanding and forecasting of TCs have paralleled the improvements in observational capabilities, such as

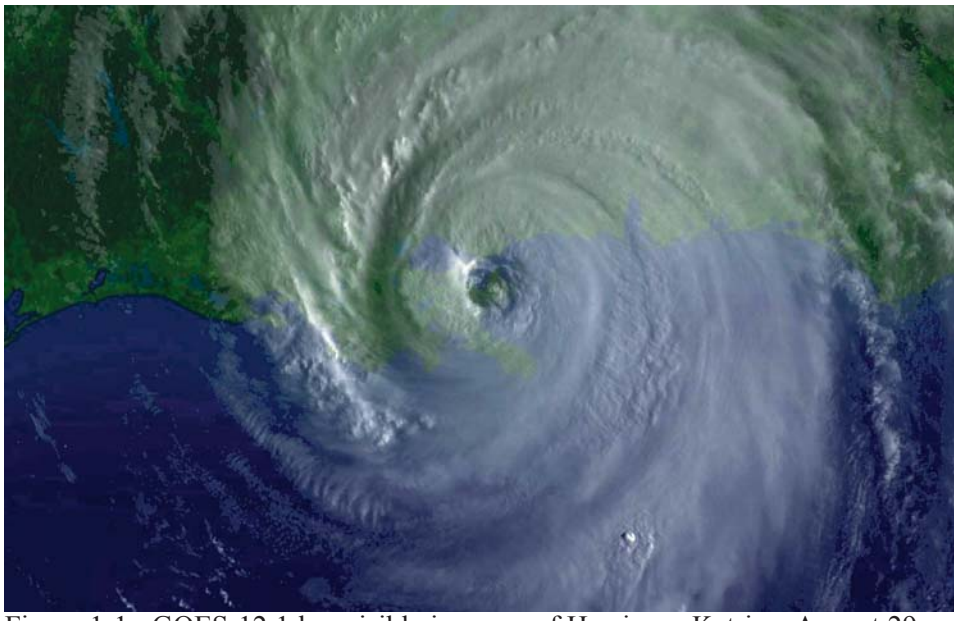

Figure 1-1. GOES-12 1 km visible imagery of Hurricane Katrina; August 29, 2005; 09:57:10. Credit: NOAA.

[1] This estimate as of May 15, 2006, is based on information from affected states' departments of health. The estimate includes direct fatalities only and does not include out-of-state evacuee fatalities included in some calculations. Fatalities by state: Louisiana 1,097; Mississippi 238; Florida 14; Alabama 2; and Georgia 2.

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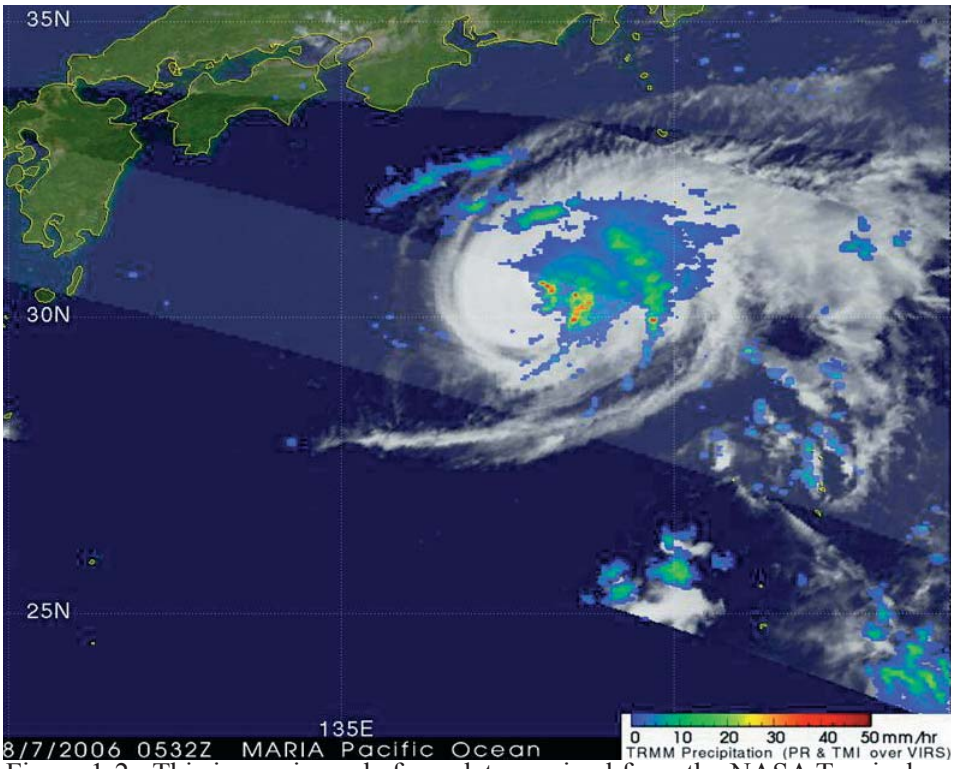

Figure 1-2. This image is made from data received from the NASA Tropical Rainfall Measurement Mission (TRMM) satellite showing Typhoon Maria closing in on Japan (August 7, 2006). Typhoon Maria subsequently weakened and passed just south of Tokyo Bay as a minimal tropical storm. Credit: NASA.

U.S. Air Force Reserve Command (53rd Weather Reconnaissance Squadron-the Hurricane Hunters) and National Oceanic and Atmospheric Administration (NOAA) instrumented aircraft (e.g., GPS dropwindsondes, stepped-frequency microwave radiometers [SFMR], airborne tail Doppler radar), satellite data, moored and drifting buoys, subsurface floats, land-based Doppler radars). The gains made in forecasting of TCs have also paralleled improvements in NWP model physics and the increased use of observations through more sophisticated data assimilation capabilities to provide improved initial conditions for the models. Nevertheless, further improvement to the Nation's TC forecast and warning service through focused research and development (R&D) are feasible, within reach, and valuable investments for our safety, security, and economic well-being. The purpose of this article is to review three projects regarding TC R&D. The projects share an ultimate goal which is to prevent loss of life and injuries associated with TCs and to reduce the Nation's vulnerability to these potentially devastating storms. Before reviewing the projects, a review of the operational TC forecast and warning centers is warranted.

OPERATIONAL TC FORECAST AND WARNING CENTERS

The TC warning service is an interdepartmental effort to provide the U.S. and designated international recipients with forecasts, warnings, and assessments concerning tropical and subtropical weather systems. The three centers that cooperate to provide this service are discussed below. Figure 3 shows the areas of responsibility for TC forecasts and warnings for the three centers: the Tropical Prediction Center/National Hurricane Center (TPC/NHC), the Central Pacific Hurricane Center (CPHC), and the Joint Typhoon Warning Center (JTWC).

TPC/NHC

The TPC is one of the twelve centers comprising the National Centers for Environmental Prediction (NCEP), a component of the NOAA National Weather Service (NOAA/NWS). Located at Florida International University in Miami, Florida, the TPC is the Regional Specialized Meteorological Center (RSMC) designated by the World Meteorological Organization (WMO) for the North Atlantic Ocean, including the Caribbean Sea and Gulf of Mexico, and the eastern North Pacific Ocean, east of longitude 140 degrees W. The TPC provides general weather guidance, as well as specialized products for aviation and marine interests in the tropics. A substantial amount of TPC/NHC's NWP model support comes from NCEP's Environmental Modeling Center. Both the TPC/NHC and the CPHC take their mission direction from the *National Hurricane Operations Plan*.

One of three major components of the TPC is the National Hurricane Center (NHC). The NHC maintains a continuous watch on TCs from May 15th in the northeastern Pacific and from June 1st in the north Atlantic through November 30th.

JTWC

The JTWC is a joint Air Force/Navy TC forecasting center. Located at Naval Base Pearl Harbor, Hawaii, the JTWC is the Department of Defense (DOD) agency responsible for issuing TC warnings for the Pacific and Indian Oceans. JTWC support encompasses more than 110 million square miles of the north and south Pacific Ocean and Indian Ocean, reaching from the west coast of the Americas to the east coast of Africa. The JTWC takes its mission direction from the Commander, U.S. Pacific Command Instruction 3140.1w (version 1w is the latest in the series). A substantial amount of JTWC's NWP model support comes from the Naval Research Laboratory (NRL) and Fleet

Numerical Meteorology and Oceanography Center (FNMOC), both located in Monterey, California.

CPHC

CPHC has forecast and warning responsibility for the central North Pacific from 140 degrees W longitude to the International Date Line. The CPHC is a component of the NOAA/NWS Weather Service Forecast Office (WFO), Honolulu, Hawaii (Figure 1-3). The Meteorologist-In-Charge, WFO Honolulu, is also the Director of the CPHC. Because the WFO Honolulu has no authorized manpower for the specialized hurricane operations of the CPHC, the center is activated only when a TC crosses into the area between 140 degrees W longitude and the International Date Line. On July 1, 2001, the WFO Honolulu was designated a WMO RSMC. Most outside support, such as model and techniques development and aerial reconnaissance, is provided through the same infrastructure that supports the TPC/NHC.

OFCM-SPONSORED PROJECT

The OFCM hosts the annual Interdepartmental Hurricane Conference (IHC), which provides a forum for the Federal agencies with operational and R&D responsibilities related to TCs, together with emergency managers and other representatives of the agencies' user communities, to review the Nation's TC forecast and warning program and make recommendations on how to improve the program in the future. One of the major objectives is to plan and prepare for the upcoming hurricane season. New procedures, procedural changes, and agreements that are approved at the IHC and are directly related to providing TC forecast and warning services are then documented for implementation in the *National Hurricane Operations Plan*. The following functional areas have been routinely included in recent IHC agendas:

- TC observations and reconnaissance.
- TC modeling and prediction.
- Impacts of TCs (e.g., winds, storm surge, heavy precipitation/inland flooding).
- TC research; science and technology.
- Transitioning TC research to operations.
- TC decision-making products and services.
- TC warning system and response.

One of the action items from the 58th IHC was to develop a comprehensive strategy for TC R&D to guide interagency efforts over the next decade. Subsequently, the Interdepartmental Committee for Meteorological Services and Supporting Research (ICMSSR) strongly supported this action. To implement the action, the Federal Coordinator for Meteorology formed the Joint Action Group for TC Research (JAG/TCR). The vision of the JAG/TCR is to maximize the potential of the TC community partnerships to improve hurricane prediction, preparedness, and resiliency for societal benefit by strategically matching research results to operational requirements. The JAG/TCR members agreed that past research planning efforts clearly outlined the TC community's priorities, objectives, and strategies, as developed and vetted through many meetings and workshops. **Therefore, the task of the JAG/TCR has been to synthesize the previous exceptional TC work, update information as needed, and develop and coordinate a comprehensive interagency strategic research plan for TCs that links research priorities to operational needs.**

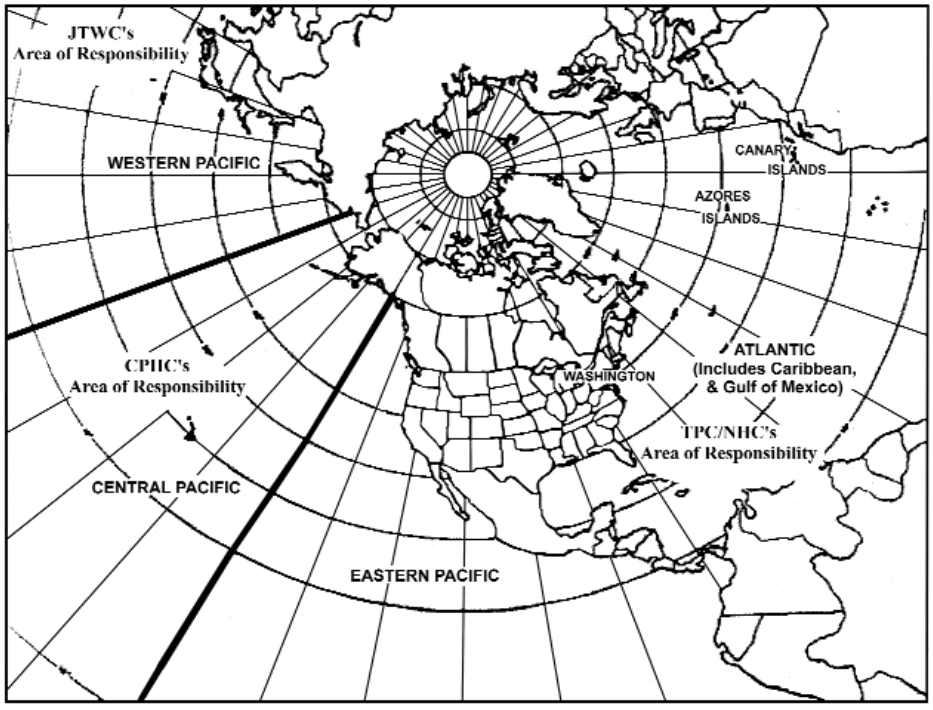

Figure 1-3. Areas of responsibility assigned to national operational forecast and warning centers. Courtesy of NOAA.

CONCURRENT TC-RELATED R&D PROJECTS

At the request of the Under Secretary of Commerce for Oceans and Atmosphere, the NOAA Science Advisory Board (SAB) formed an external group to conduct a review of NOAA's hurricane intensity research, development, and transition to operations. The panel became known as the NOAA SAB Hurricane Intensity Research Working

Group (HIRWG). In another hurricane-related project, the National Science Board (NSB), the governing board of the National Science Foundation (NSF), formed the Task Force on Hurricane Science and Engineering (HSE). The task force examined the "hurricane problem" in a more holistic manner, considering physical, social, behavioral, economic, biological, ecological, information technology, and other appropriate sciences, as well as engineering (e.g., civil, environmental, mechanical) disciplines. Two questions incorporated into their review were:

1. To what extent does the Nation understand the hurricane as an integrated science and engineering problem?
2. How can such understanding be used to improve the Nation's ability to predict, mitigate, and react?

To ensure that these three efforts-NOAA/SAB, NSF/NSB, and OFCM's JAG/TCR-were aware of, and able to learn from, each other, the OFCM planned a workshop during the 60th IHC, held in Mobile, Alabama, entitled *Tropical Cyclone Research: Priorities for the Next Decade*. The workshop was moderated by Dr. Robert Serafin, National Center for Atmospheric Research Director Emeritus and Chair of the Board on Atmospheric Sciences and Climate. Dr. Michael Crosby, Executive Officer for the NSF/NSB, provided an update on the Task Force on HSE. Following Dr. Crosby, Dr. John Snow, College of Geosciences, University of Oklahoma, presented an update on activities of the NOAA/SAB HIRWG. The last item in the research workshop was a review of an early version of the JAG/TCR's draft interagency strategic research plan for TCs. Dr. Frank Marks (NOAA/AOML /HRD) and Ms. Robbie Hood (NASA Marshall Space Flight Center, Global Hydrology and Climate Center), cochairs of OFCM's JAG/TCR, along with Dr. Naomi Surgi (NOAA/NWS /NCEP/EMC), led this portion of the workshop. The workshop was of great benefit to all three project groups, and other participants at the workshop were able to hear about, and interact concerning, these complementary ongoing efforts.

MORE DETAILS ON THE JAG/TCR WORK

In addition to the workshop held at the IHC (described above), the JAG/TCR kept abreast of the work of the two other projects. This section provides additional details of the work of the JAG/TCR and their document, *Interagency Strategic Research Plan for Tropical Cyclones*: *The Way Ahead.* The plan:

- Illustrates the fundamental rationale for continuing the effort in TC R&D that has produced major improvements in forecasts and warnings in recent years. It introduces the R&D community that supports the three operational TC forecast and warning centers.
- Describes in more detail the major players in the TC R&D community and how they interact with each other and with the operational centers. It also reviews recent and concurrent planning activities that are significant for formulating a community strategy.
- Assesses the Nation's current capability and limitations of the Nation's TC warning service. These capabilities constitute a classic end-to-end system for environmental observing, modeling and interpretation, communication of products and information, and end-user education and outreach-albeit one focused on the environmental threats posed by TCs. The capabilities assessment therefore begins with the key operational observing systems, progresses to the operational models and systems for assimilating data into them, and then discusses the forecast and warning information dissemination system, including current efforts in end-user education and outreach.
- Uses the same end-to-end system structure to present the JAG/TCR's perspective on the future capabilities required to meet both current operational needs and emerging needs identified by the operational centers. The future capabilities section reviews several potential improvements to the observational capabilities, including the National Aeronautics and Space Administration's Global Precipitation Measurement Satellite, the Constellation of Observing Satellites for Meteorology, Ionosphere, and Climate (COSMIC) satellites (see Figure 1-4), and land-based Multifunction Phased Array Radar (MPAR). The future capabilities section also reviews DOD and NOAA NWP plans. These future capabilities are translated into a set of research priorities, around which a comprehensive R&D strategy for the next decade can be built.

The overarching research priorities established by the JAG/TCR included tropical cyclone intensity and structure (wind radii); track; other landfalling impacts (sea state and storm surge, precipitation, and inland flooding); social science research; and intraseasonal and inter-annual variability.

- Presents the JAG/TCR recommendations for next steps that can be taken by the cognizant Federal agencies and coordinating entities to begin implementation of this strategy.

SUMMARY

While tropical cyclone forecasting has been and continues to be a challenge, as we move forward over the next decade we can expect continued improvements in TC forecasting. As detailed in the *Interagency Strategic Research Plan for Tropical Cyclones: The Way Ahead,* the capability to gain skill in forecasting intensity and structure, sea state and storm surge, and precipitation is now on the horizon much

like improving track was a decade ago. The gain in skill is due to continued improvements in observational capabilities and further advancements in NWP model physics and data assimilation systems.

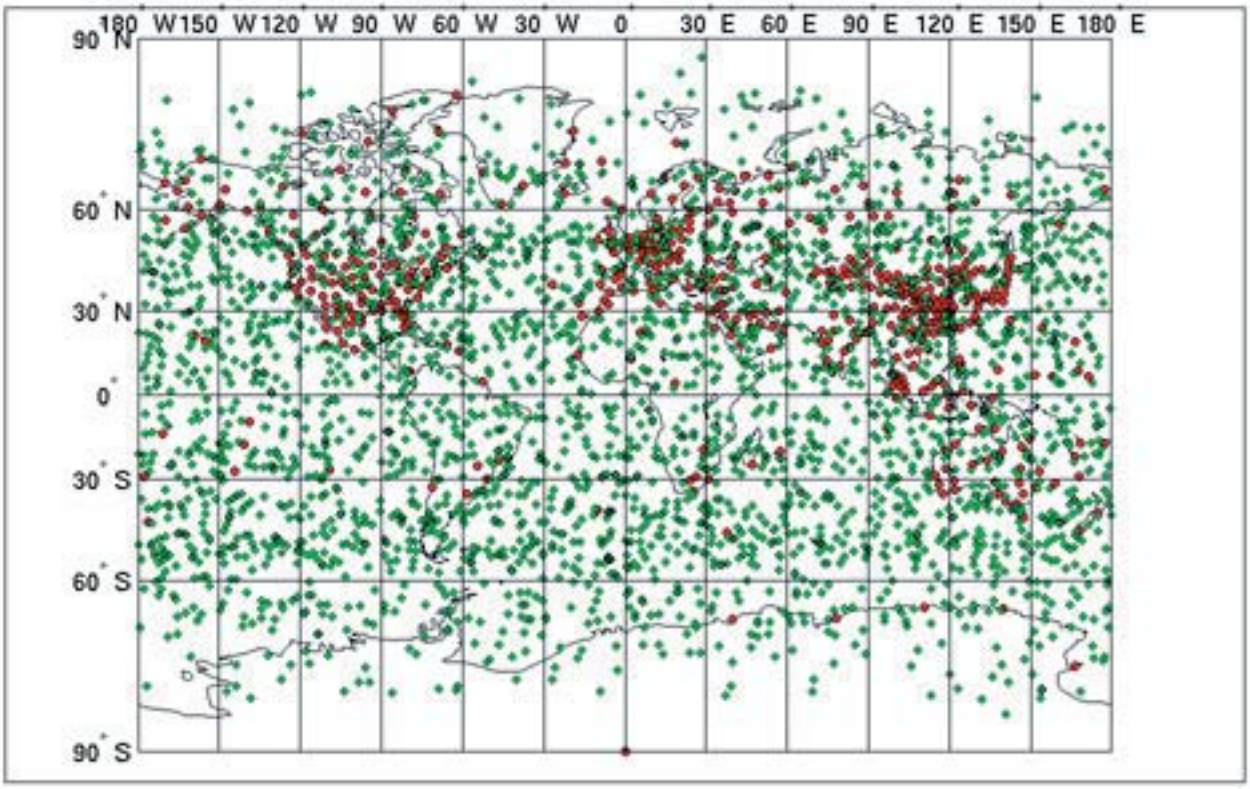

Figure 1-4. A comparison of the current global coverage of instruments launched via radiosondes each day (in red) with the expected coverage from the COSMIC satellite network in a 24-hour period (in green). Credit: COSMIC.